Final Technical Report to

the Air Force Office of Scientific Research

for the Project:

"High Power, Ultra-Long-Pulsed Gyrotron Backward Wave Oscillators"

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submitted by:
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ABSTRACT

The objective of this research program was to explore tapering of interaction tubes and magnetic fields as techniques for enhancing the performance of high power microwave gyrotron-backward-wave-oscillators (gyro-BWOs). Experiments were performed on the Michigan Electron Long-Beam Accelerator, (MELBA), which operated with parameters: voltage=0.7-0.9 MV, diode current = 1-10 kA, injected current = 1-4 kA, and pulselengths of 0.5-1 microsecond. Microwave emission frequency was in the range from 4.5-6 GHz. Experiments on the fundamental cyclotron wave showed peak microwave tube power up to 40-55 MW over shortened pulselengths (<100 ns). Longer pulse microwave emission was obtained at lower powers (multi-MW). The second harmonic gyro-BWO emission spectrum was also measured at ~MW power levels. The microwave spectral width was < 200 MHz (<3.7%) for uniform B field with uniform or tapered tubes. Widened spectra of 200-400 MHz (<7.4%) were measured for tapered magnetic fields with uniform or tapered tubes.

Modeling was performed with the MAGIC code to guide the experiments. Results showed qualitative agreement between TE_{11} mode experiments and TE_{01} MAGIC Code simulations, regarding microwave power versus tapering direction and scaling.

Research collaborations between UM and the Phillips Lab were extensive. During August of 1993, two scientists from Phillips Lab traveled to Michigan to perform experiments on MELBA which measured the microwave spectrum of fundamental cyclotron mode radiation emitted from tapered-versus- uniform-tube gyro-BWOs; these results were published. T.A. Spencer also served as a member of the doctoral committee of Mark T. Walter.

1.0 Introduction

The Air Force requires high power microwave sources which span the frequency range from 1-300 GHz. One type of tunable microwave source which has promise over a large part of the frequency spectrum is the gyrotron class of devices. In particular, the gyrotron-backward-wave-oscillator has promise because of the following features:

1) Operation near cutoff gives insensitivity to e-beam velocity spread, (an advantage for explosive emission, cold cathodes),

2) Frequency-tunable by magnetic field, beam voltage or alpha ($V_{\perp}/V_{||}$), and

3) Smooth wall reduces microwave breakdown.

The research project described here outlines the major findings of a 41-month series of experiments and code simulations to investigate whether the high power and long-pulse capabilities of the gyro-BWO could be extended by tapering of magnetic fields and radius in tubular structures.

2.0 Progress on Research During AFOSR Grant

2.1 Experimental Configuration

The experimental setup for the tapered-magnetic field gyro-BWO is presented in Figure 1. The electron beam is generated from a velvet button, explosive-emission cathode affixed to the end of a glyptal-coated, hemispherical-end cathode stalk; this cathode has been demonstrated to produce very low plasma closure velocities and voltage droop. The magnetic field system includes four separate sets of coils:

1) Large, pancake solenoids which produce about 1 kG magnetic field in the diode region (driven by a capacitor bank at 1.8 kV),

2) Solenoidal magnetic field coils, wound directly around the vacuum tube (driven by a double polarity, Marx circuit, electrolytic capacitor bank),

3) Correction coils to cancel the spatial decay of the diode coils (connected in series with the diode coils),

4) Tapering trim-coils (of different winding-pitch), which can be connected for positive or negative magnetic tapering.

After the e-beam leaves the interaction region, it is dumped to the chamber walls by two large permanent magnets.

The microwave extraction is accomplished by a bevel-cut S-band waveguide at the upstream (backward-wave) end of the tube. Microwave output power is reduced by directional couplers and either split into G-band and H-band channels or sent to the Faraday cage on coaxial cables for frequency filter measurements.

The conventions on tube tapering and magnetic tapering are shown in Figure 2. Tapered tubes were made of thin copper sheet, which enabled fast penetration of pulsed magnetic fields. The median radius of the tubes was 1.9 cm.

The desired gyro-BWO dispersion relation is depicted in Figure 3. The fundamental gyrotron-backward-wave interaction for the desired TE_{11} mode is at a frequency of about 4.8 GHz for this magnetic field of 4.5 kG.

2.2 Experimental Results

This section summarizes the results of the gyro-BWO experiments over the entire 3 year, 5 month program. Typical MELBA waveforms are presented in Figure 4. The electron beam voltage overshoots to about 900 kV, followed by a slight undershoot of ~750 kV; later on in the pulse the voltage becomes very flat. The e-beam current is also quite flat for this cathode. Microwave emission was typically long-pulse during the undershoot, as shown in the figure; highest power spikes ($\leq$100 ns) were typically measured on the initial overshoot.

A summary of peak power for individual shots, for the case of a *uniform magnetic field and uniform interaction tube* is given in Figure 5. The highest tube power (~33 MW) from the peak extracted power shot (6.6 MW) is obtained by assuming the peak, -7 dB coupling between the tube and the extraction waveguide. A broad power peak can be seen at about 4,600 Gauss, however, the scatter in the data makes it difficult to compare these data to the MAGIC code results. Therefore, the data was smoothed by averaging over 100 Gauss bins, as shown by the smooth line drawn over the data.

Negative tapering of the tube radius, with uniform B field, was predicted by MAGIC code to yield an improvement in gyro-BWO microwave power. Comparison of tapered tube data with MAGIC simulations results are given in Fig. 6a and 6b; MAGIC code power is normalized to experimental power at zero taper. It can be seen that, the general shape and amplitudes of the curves are similar, even though the horizontal scale appears slightly "out-of-phase" versus taper %. This may be a consequence of the fact that the experiment operated in the TE_{11} mode, whereas the code was run for the azimuthally symmetric TE_{01} mode. The optimal, experimental power and energy for this case is for the 10% downtapered tube with a uniform magnetic field.

Gyro-BWO experimental emission data for the *tapered magnetic field with a uniform tube,* are shown in Figure 7, for comparison with MAGIC code simulations. Agreement between code and experiments was initially poor; a closer analysis revealed that the negative tapered B field data probably contained some regions of positive taper, as shown in Figure 8. When the region of positive taper was eliminated, the measured microwave power was closer to the trend predicted by MAGIC; this is shown as the vertical dotted lines in the figure. Thus, the experimental data showed the same trends as MAGIC code simulations for both tapered tubes/uniform B as well as tapered B/uniform tubes.

2.3 MAGIC Code Simulations

Magic Code simulations were used to guide the gyrotron-backward-wave-oscillator experiments. As in the past, these simulations were run for a scaled TE_{01} mode (instead of the experimental TE_{11} mode) to indicate the effects of tapered magnetic fields and tapered tubes. The particle trajectory plot, showing the simulation geometry is presented in Figure 9; as seen in the figure, the gyro-emission e-beam is deflected to the tube wall after the interaction region. (More details on the modeling techniques were presented by Mark Walter in the MAGIC User Group Meeting in Madison, Wisconsin at ICOPS; also see proceedings compiled by Mission Research Corp. and a paper for submission to the Special Issue on High Power Microwaves of the IEEE Transactions on Plasma Science). The time history of Etheta is shown in Figure 10, indicating that rapid growth and saturation occurs. The microwave frequency of the FFT in Figure 11 shows that the MAGIC code's radiation originates from the fundamental gyro-BWO.

A summary of the MAGIC Code modeling of the gyro-BWO for tapered magnetic field and interaction tube radii is presented in Figure 12. This plot clearly shows that a positive-tapered magnetic field (optimized at 7.5%) results in increased microwave power. The intuitive explanation for positive-B-tapering providing enhanced power is that an increasing B field allows the higher energy electrons (initially accelerated by the wave) to fall back into resonance and emit their energy. One could argue that there is more to be gained by recovering energy from the accelerated electrons than by attempting to recover more energy from the lower energy electrons which have already emitted. For the perfectly cold e-beam of the computer model, the uniform tube radius has the highest power;

experimentally, we observed maximum power for negative-tapered-radii, showing that radius tapering is advantageous for a real, hot, e-beam with large alpha spread.

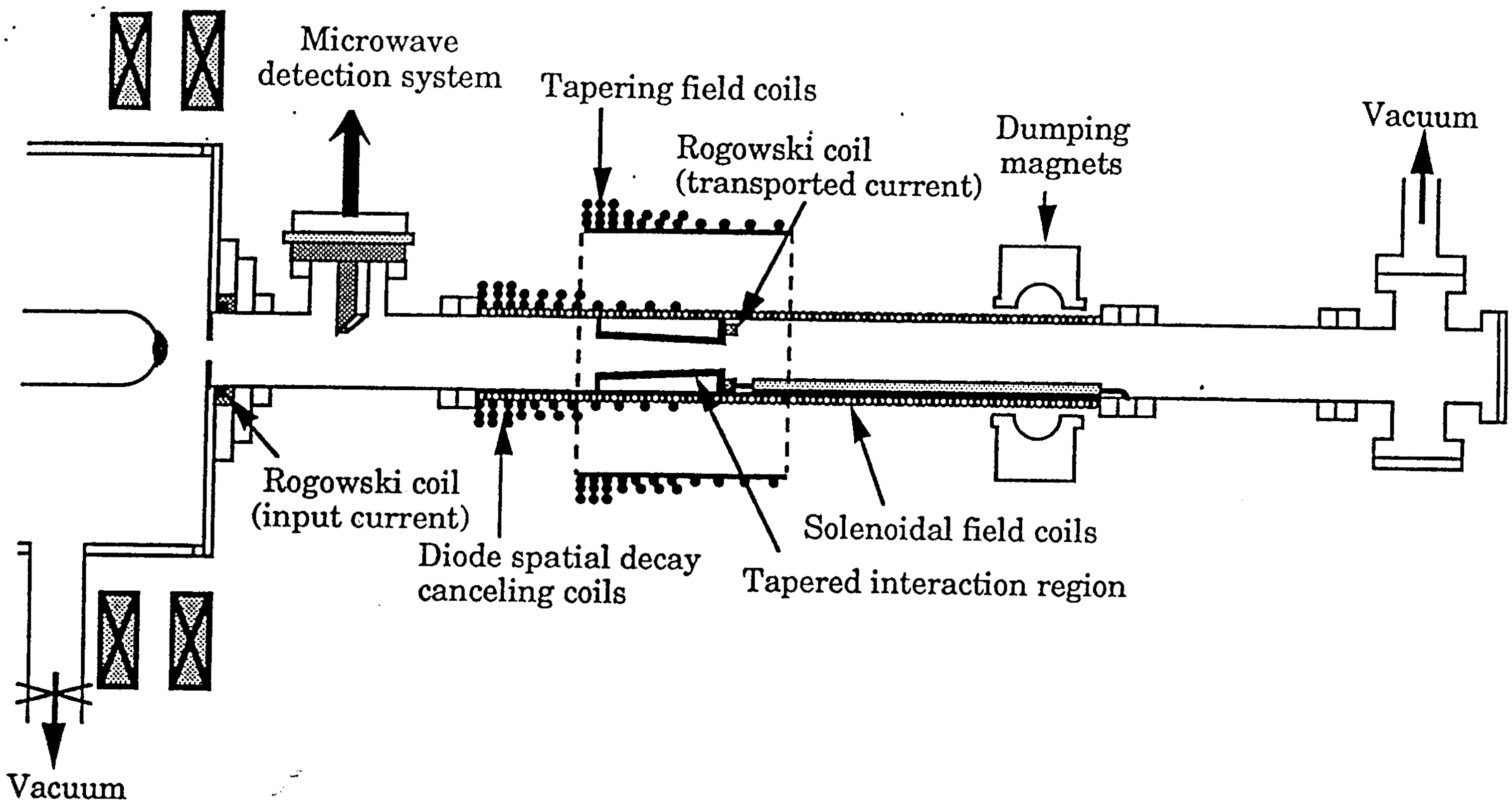

Figure 1. Experimental setup for tapered interaction region and tapered magnetic field experiments.

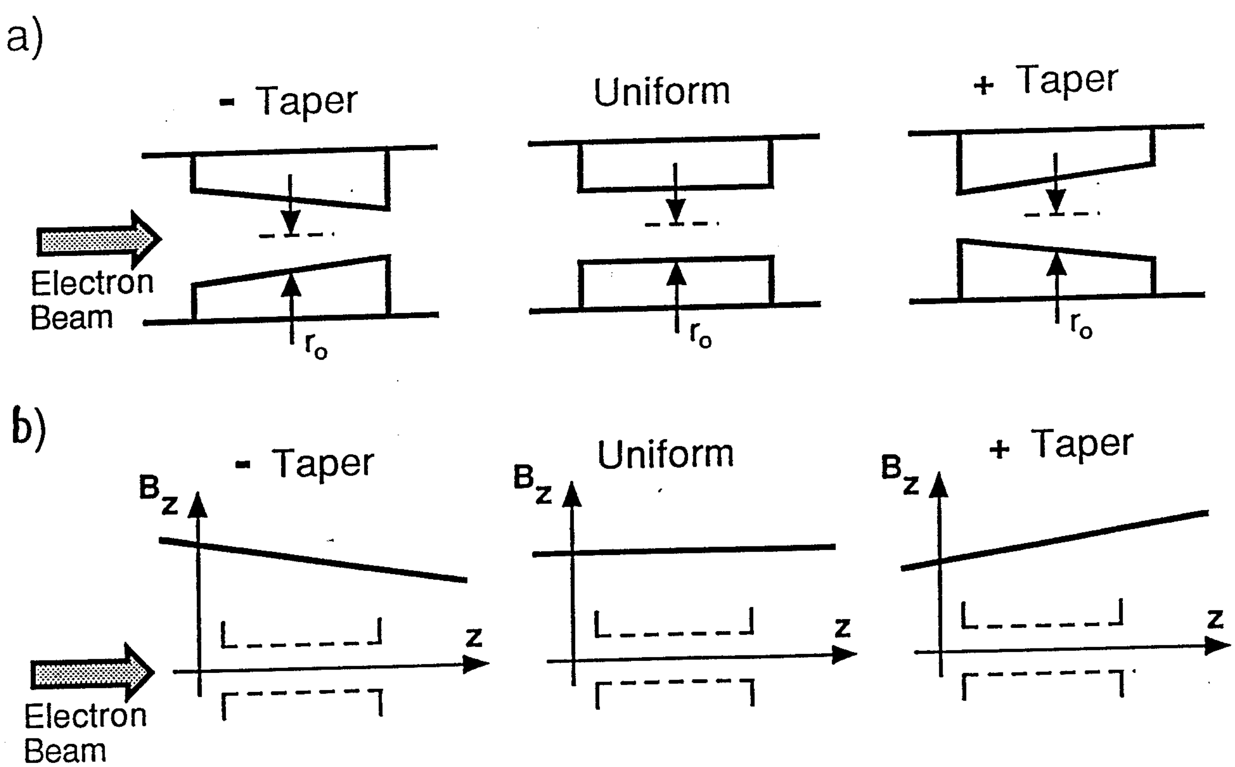

Figure 2 Convention used in describing a) tapered interaction regions and b) tapered magnetic fields.

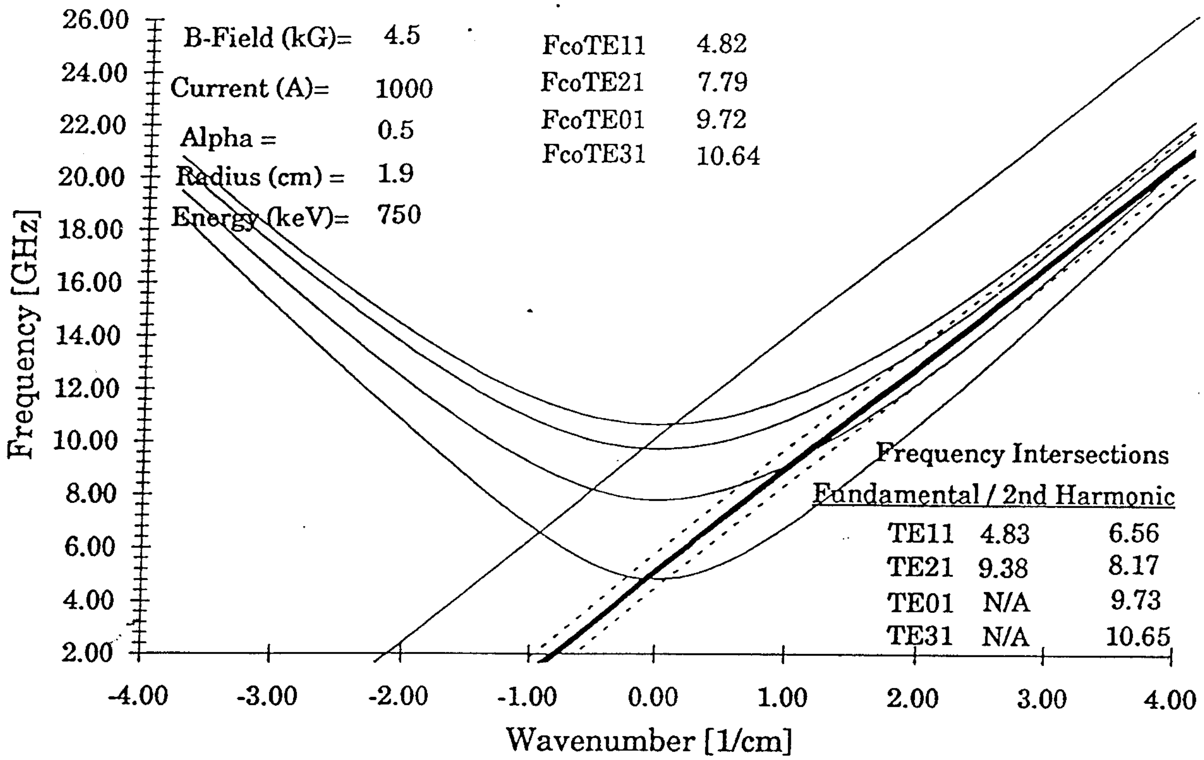

Figure 3. Dispersion relation of the electron beam cyclotron wave within the uniform interaction region (r=1.9 cm). Dotted lines indicate the effect of -10% tapered magnetic field on the fundamental beam line (thick line).

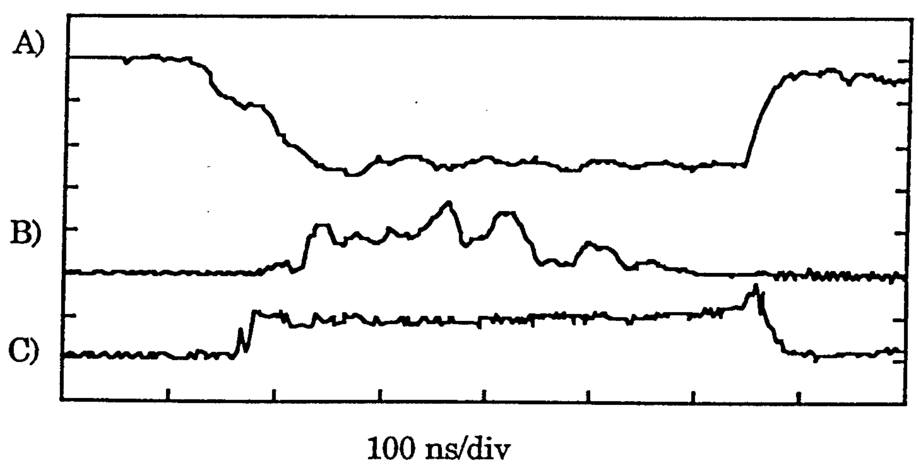

Figure 4. MELBA shot data from M2857; a) MELBA voltage 310 kV/div, b) Extracted G-band microwave power 0.4 MW/div, c) Aperture current 0.5 kA/div.

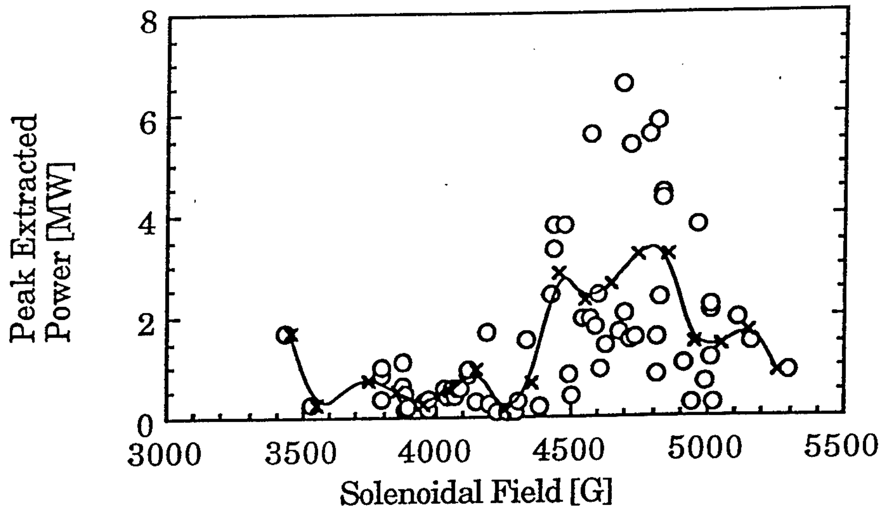

Figure 5 Summary of G-band power measurements made for the uniform interaction region in a uniform axial magnetic field. The axial field magnitude at the center of the interaction region is plotted along the horizontal axis.

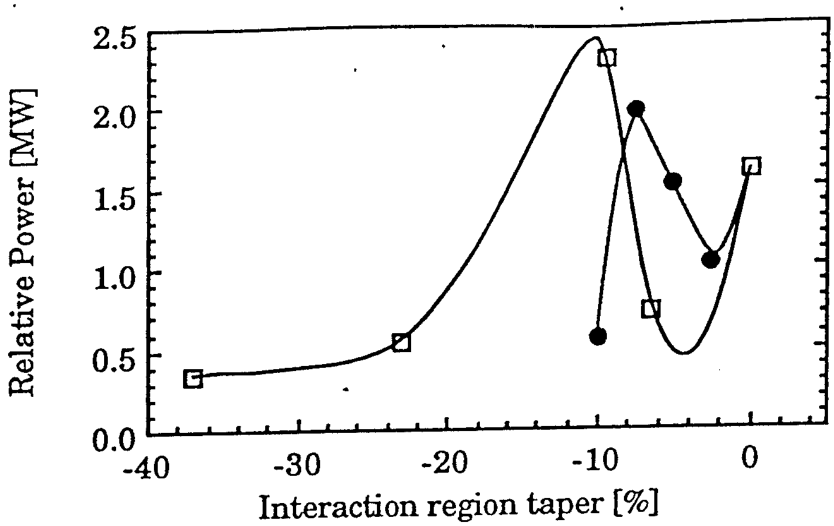

Figure 6a. **Summary of bin averaged G-band power from negative tapered interaction regions in identical axial field profiles. Plotted squares are from experimental data. Circles denote relative power predicted by MAGIC simulation normalized to the uniform tube power value.**

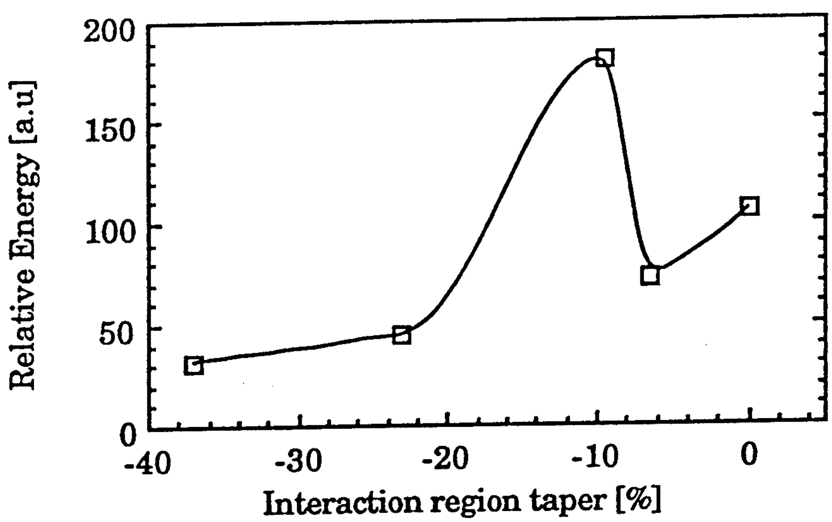

Figure 6b. **Summary of bin averaged relative energy from negative tapered interaction regions in identical axial field profiles.**

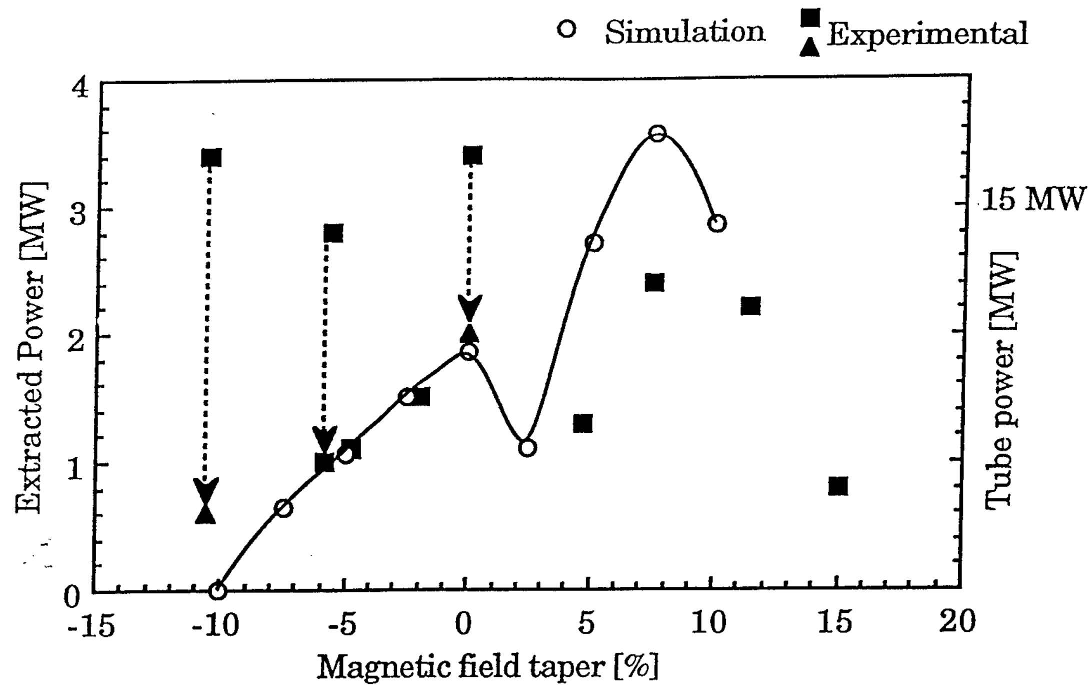

Figure 7 Summary of bin averaged G-band power from tapered magnetic fields for the uniform interaction region. Plotted squares are from experimental data. Triangles indicate improved linear fit magnetic field experimental data. Circles denote relative power predicted by simulation.

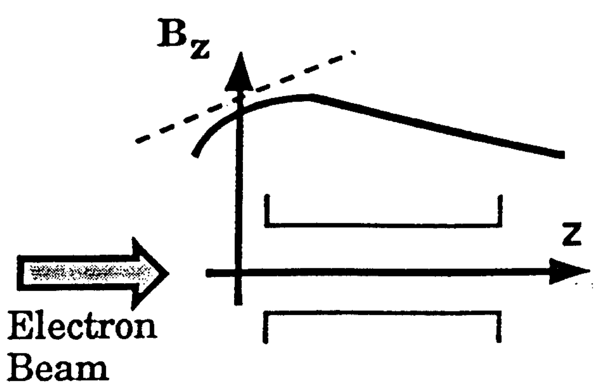

Figure 8. Schematic representation of steep negative tapered magnetic field. Dashed line indicates positive tapered field region at the interaction region entrance.

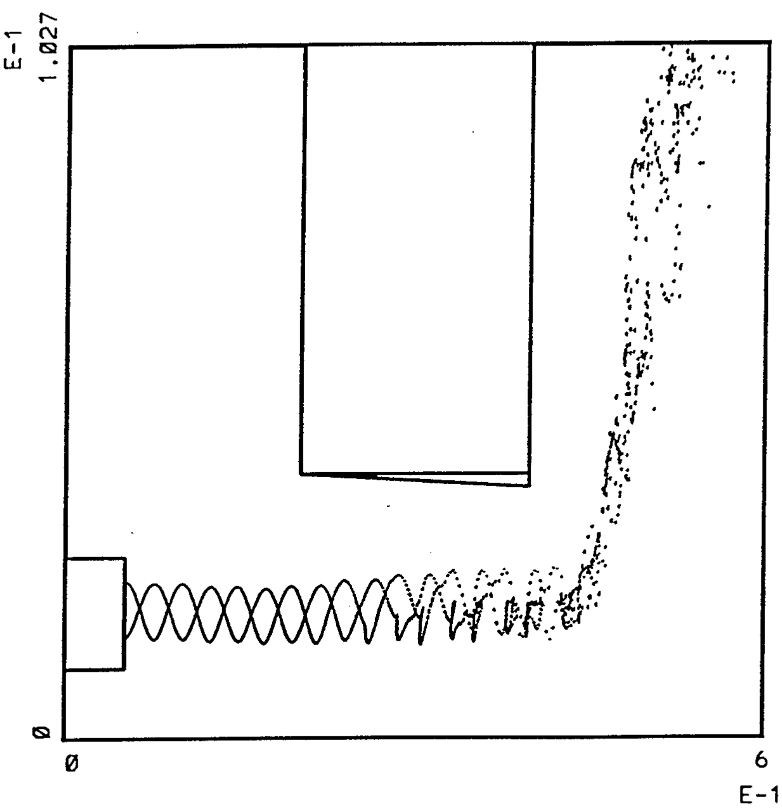

Figure 9. **Snapshot of particle trajectories plotted 100 ns into the simulation showing beam deflection to the drift tube wall.**

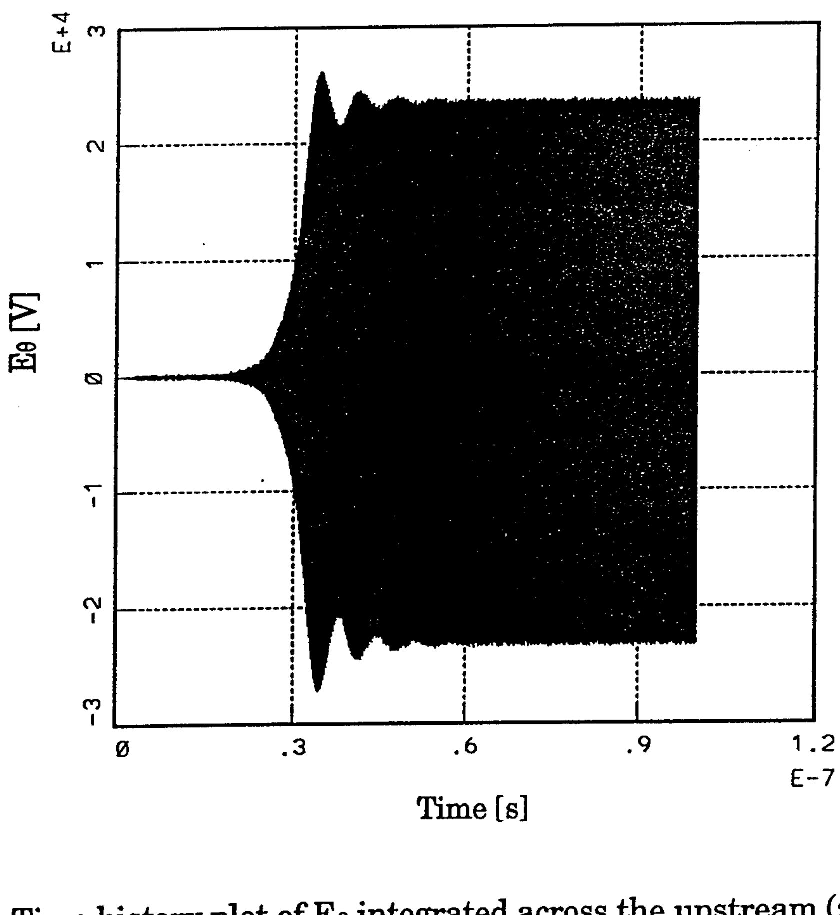

Figure 10. Time history plot of E_θ integrated across the upstream (z=20 cm) end of the interaction region above the beam. Note that field saturation occurs at approximately 35 ns.

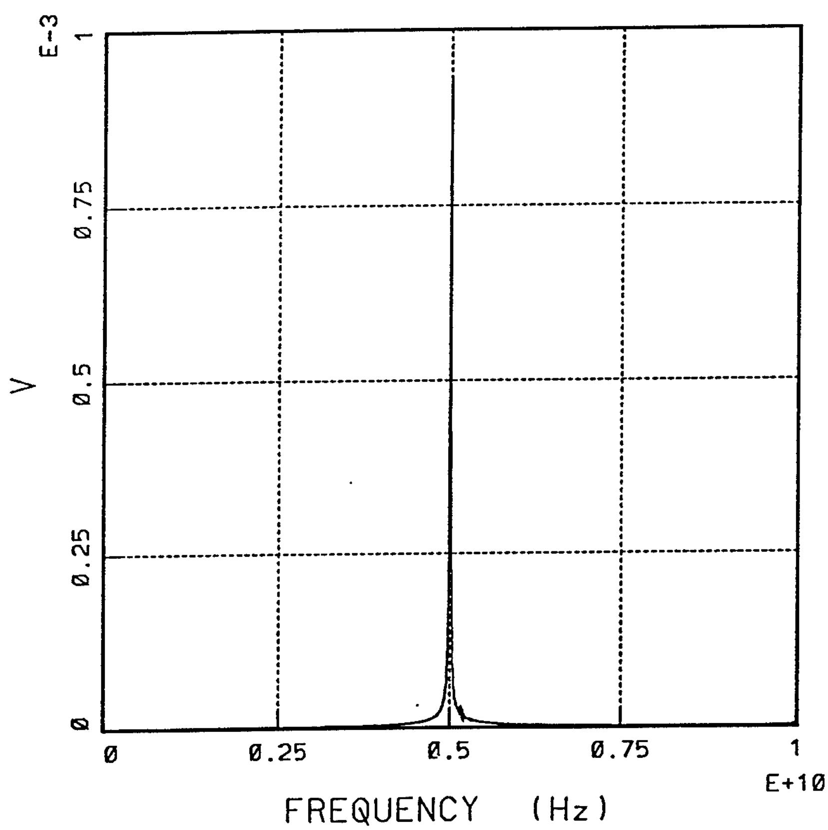

Figure 11. **The fast Fourier transformation of E_θ indicates power flow at the expected fundamental TE_{01} frequency.**

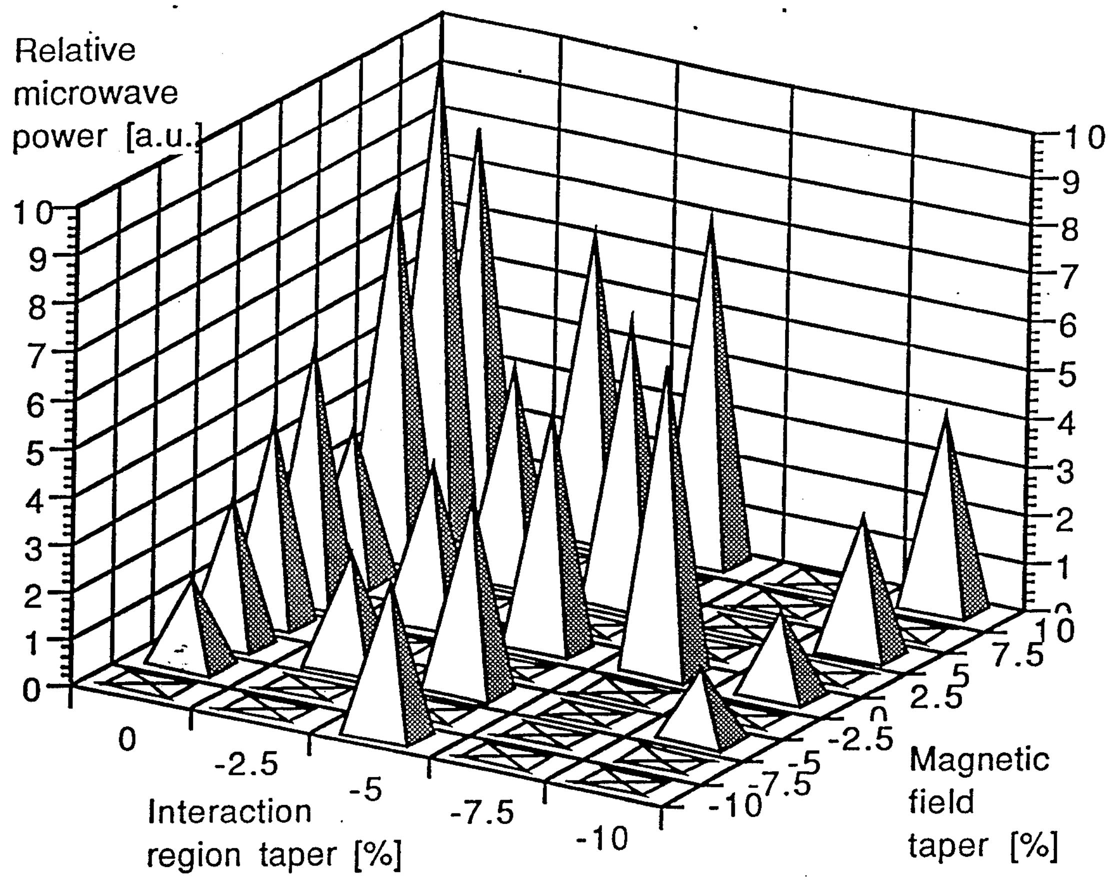

Figure 12 Summary of Poynting flux for all TE modes (S_{TE}) as a function of magnetic field taper and interaction region taper.

3.0 Doctoral Dissertations, Papers Submitted and Conference Papers Presented

Doctoral Dissertations

Mark T. Walter, "Effects of Tapering on High Current, Long-Pulse Gyrotron Backward Wave Oscillator Exeriments", defended May 11, 1995

Papers Published/ Submitted to Refereed Journals

1) "Effects of Tapered Tubes on Long-Pulse Microwave Emission from Intense e-Beam Gyrotron Backward-Wave-Oscillators", M. T. Walter, R. M. Gilgenbach, P. R. Menge, and T. A. Spencer, IEEE Transactions on Plasma Science, 1994 Special Issue on High Power Microwave Generation, Vol. 22, pages 578-584, 1994

2) "Effects of Tapering on Gyrotron Backward Wave Oscillators: *Part I Computer Simulations",* M. T. Walter, R. M. Gilgenbach, J. Luginsland, J. Hochman, R. Jaynes, Y.Y. Lau, and T.A. Spencer, to be submitted to IEEE Transactions on Plasma Science, Special Issue on High Power Microwave Generation, expected publication date of June 1996

3) "Effects of Tapering on Gyrotron Backward Wave Oscillators: *Part II Experiments",* M. T. Walter, R. M. Gilgenbach, J. Luginsland, J. Hochman, R. Jaynes, Y.Y. Lau, and T.A. Spencer, to be submitted to IEEE Transactions on Plasma Science, Special Issue on High Power Microwave Generation, expected publication date of June 1996

Conference Papers Presented

1) "Gyrotron Backward Wave Oscillators Driven by a Microsecond Electron Beam Accelerator", Presented at the 1992 IEEE International

Conference on Plasma Science, June 1-3, 1992, Tampa, Florida

2) "High Power, Long-Pulse Intense e-Beam, Gyrotron-Backward Wave-Oscillators", presented at the 17th International Conference on Infrared and Millimeter Waves, Dec. 14-18, 1992

3) "High Power, Long-Pulse Gyrotron Backward Wave Oscillator Experiments Utilizing Microsecond Intense e-Beams", presented at the 1992 meeting of the Division of Plasma Physics of the American Physical Society, Nov. 16-20, 1992

4) "Tapered Tube, Microsecond Electron Beam Gyrotron-Backward-Wave-Oscillators", presented at the 1993 Particle Accelerator Conference, May 17-19, 1993, Washington, D.C.

5) "Tapered Gyrotron-Backward-Wave Oscillators for High Power, Long-Pulse Microwave Generation", R. M. Gilgenbach, M. Walter, P.R. Menge, and T.A. Spencer, Presented at the IEEE International Conference on Plasma Science, June 7-9, 1993 in Vancouver, BC

6) "Effects of Tapered Interaction Tubes on Long-Pulse Intense e-Beam Gyrotron-Backward-Wave-Oscillators, R. M. Gilgenbach, M. T. Walter, P. R. Menge, and T. A. Spencer, Presented at the 9th IEEE International Pulsed Power Conference, June 21-23, 1993, Albuquerque, NM; published in proceedings

7) "Tapered Gyrotron-Backward-Wave-Oscillator Utilizing Intense, Microsecond Electron Beams", R. M. Gilgenbach, M. T. Walter, P. R. Menge, Y. Y. Lau, and T. A. Spencer, Presented at the Vacuum Electronics Annual

Review, June 29-July 1, 1993, Crystal City, VA ; published in proceedings

8) "Magnetic Tapering and Tapered Tubes in Microsecond Electron Beam Gyrotron-Backward-Wave-Oscillators", M. T. Walter, R. M. Gilgenbach, P. R. Menge, and T. A. Spencer, Presented at the 1993 Annual Meeting of the Division of Plasma Physics of the APS, November 1-5, 1993, St. Louis, MO

9) Magnetic Tapering of Intense e-beam, Long-Pulse Gyro-BWOS", M. . Walter, R.M. Gilgenbach, J. Hochman, T.A. Spencer, Presented at the 1994 IEEE International Conference on Plasma Science, Santa Fe, NM , 6-8 June, 1994

10)" Tapering of Gyrotron-Backward-Wave-Oscillators Driven by Microsecond, Intense e-Beam", M. T. Walter, R. M. Gilgenbach, J. Hochman, C. H. Ching, J. Luginsland, and T. A. Spencer, Presented at the 1994 Annual Meeting of the Division of Plasma Physics of the APS, November 7-11, 1994, Minneapolis, MN

11) Effects of Magnetic Tapering and Tapered Tubes on Long-Pulse, Intense e-Beam Gyro-BWO Microwave Emission", M. T. Walter, R. M. Gilgenbach, J.I. Rintamaki, J. Luginsland, J. Hochman, R. Jaynes, Y.Y. Lau, and T.A. Spencer, Presented at the 1995 IEEE International Conference on Plasma Science, June 5-8, 1995 in Madison, WI

12) "Effects of tapered magnetic fields and structures on long-pulse, gyrotron-backward-wave oscillator performance", R.M. Gilgenbach, M.T. Walter, J. Hochman, J. Luginsland, J. Rintamaki, R. Jaynes, and Y.Y. Lau, Presented at the 1995 SPIE Meeitng in San Diego, CA, July 10-13, 1995

4.0 Personnel Involved in Research

Faculty

R. M. Gilgenbach, Professor and Lab Director

Graduate Students

Mark T. Walter, Ph. D. graduate, now at University of Maryland

P. R. Menge, Ph. D. graduate, now at Sandia National Lab

Jonathan Hochman, Ph.D. Precandidate

Reginald Jaynes, M.S. Degree candidate

Phillips Lab Collaborator

Dr. Thomas Spencer

5.0 Honors and Awards

R. M. Gilgenbach received the Excellence in Research Award (1 of 3 awarded) from the College of Engineering in late January 1993.

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